DOE/UTRC Advanced Microturbine System

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T. Rosfjord

Pratt & Whitney Canada
Detroit Edison Energy Technologies
Hamilton Sundstrand
SatCon
ORNL

D.Haught and S. Waslo
U.S. Department of Energy, Office of Power Technologies
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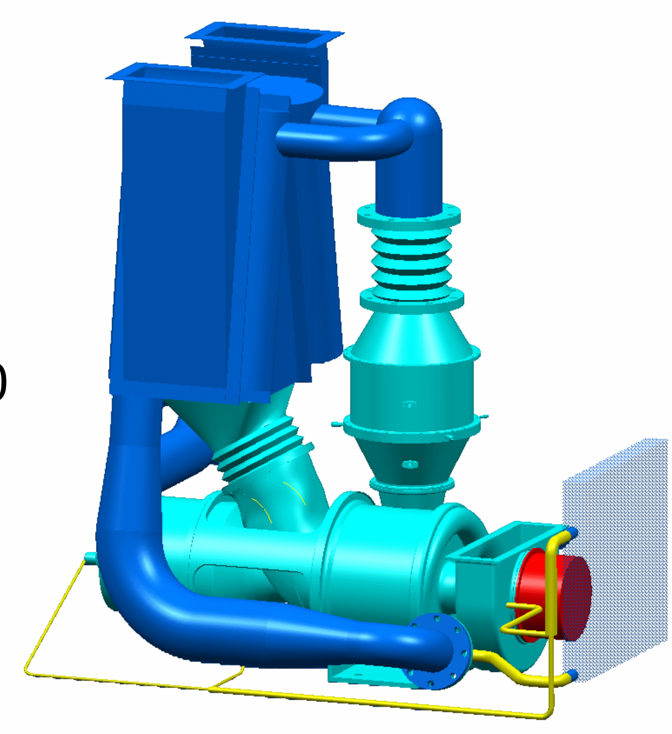
Agenda

- Program goals and approach
  - Market motivation
- Cycle for affordable, 40% microturbine system
  - Improved economics
- Progress in reducing system risks
  - Ceramic turbine
  - Low emissions combustor
  - Organic Rankine Cycle
- Plans for 2002 and Beyond
- Summary

UTRC Program Builds on PWC ST5-Powered ENT400

DOE Advanced Microturbine System Goals

- Electrical efficiency = 40%
- NOx = 7 PPM on natural gas fuel
- Multi-fuel capability
- 11,000 hour between major overhaul
- System cost = $500US/kW



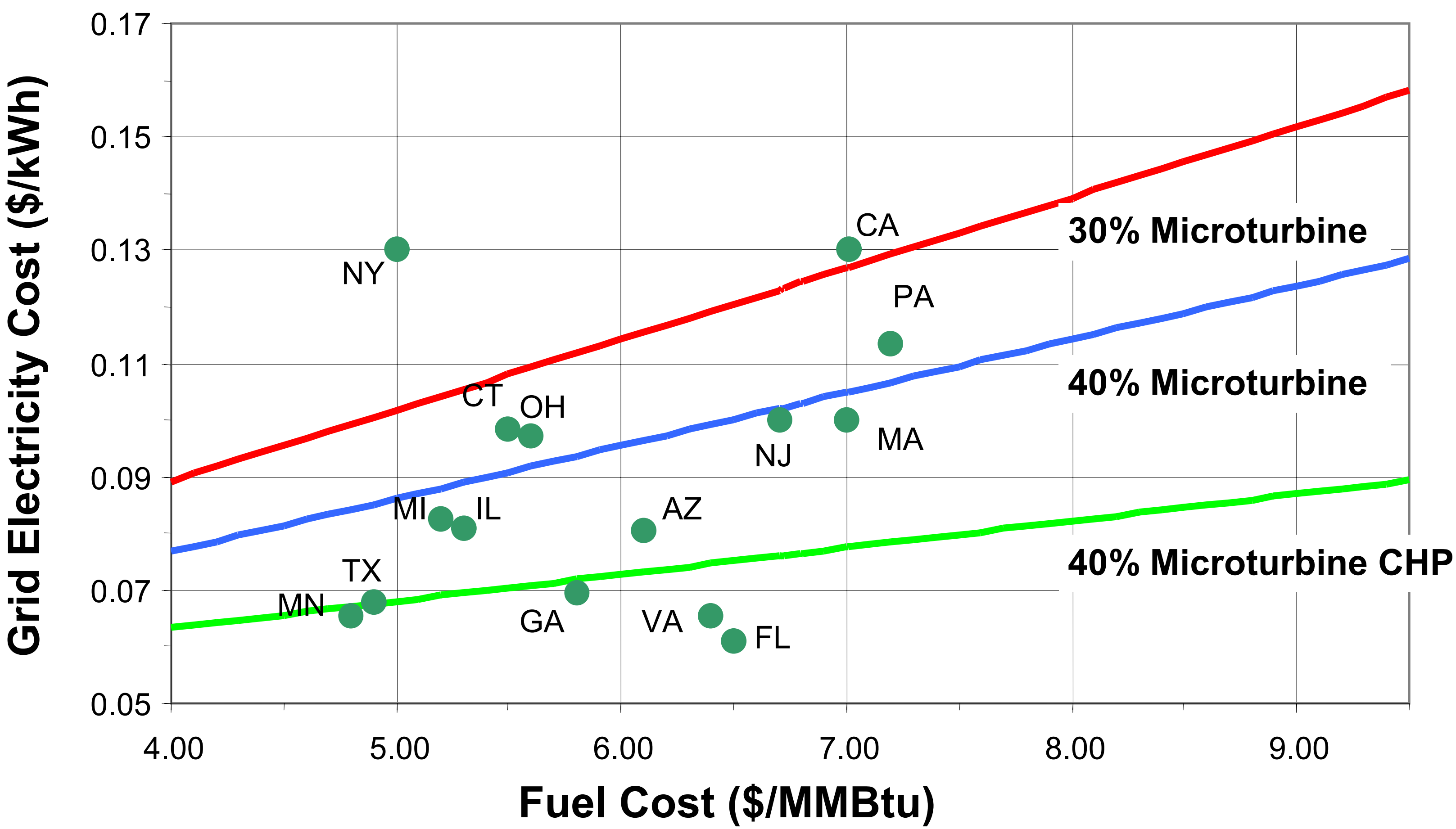
UTRC Approach

- Affordably increase PWC ST5-powered ENT400 microturbine from 30% to 40% electrical efficiency with NOx < 7 ppm

40% Microturbine Competitive in Many States

Attractive economics for > 30% of US population

- 4-year customer payback of installed equipment @ $700/kW
- No credit taken for reliability, low emissions, or avoided transmission upgrade



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UTRC Program Stages Advanced Microturbine Development

Proceeds from system definition through field demonstration

Task 1   Preliminary Design (Oct 00 – Dec 01)

- System identification to meet goals
- Preliminary Design of Ceramic Turbine, Low Emissions Combustor, Electric Generator, ORC to ensure

Task 2 Subsystem Component Development (Apr 01-Jun 03)

- Technology risk-reduction for turbine, combustor, ORC

Task 3 & 4 System Integration and Evaluation (Feb 02-Apr 04)

- Assemble and demonstrate system technology-readiness
  - Initial system with ORC
  - Final system with all technologies

Task 5 Durability Demonstration (Jan 05-Sep 05)

- Run complete system in the field for >4000 hr

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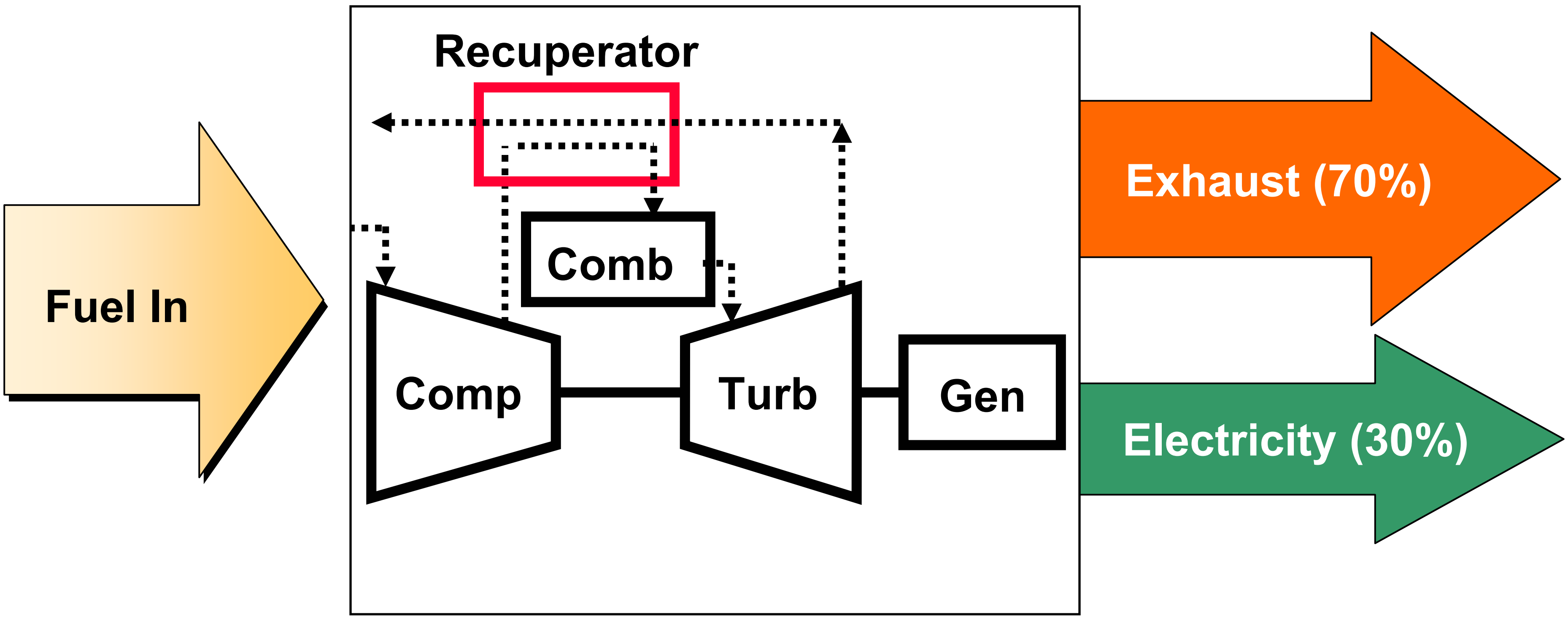
Right System Delivers Affordable Performance

System study combined performance and economics

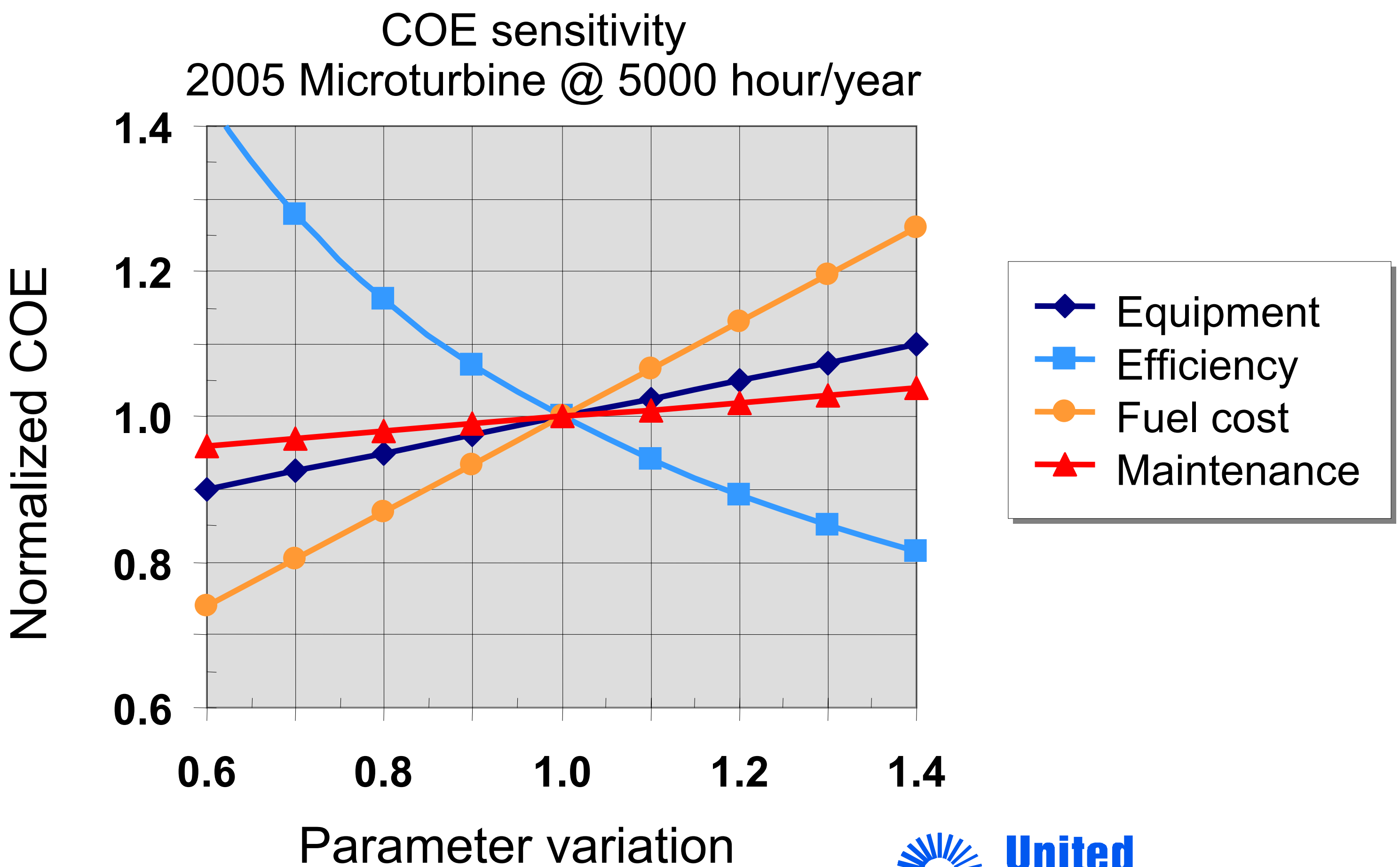
- PWC ST5 drives a 30% electrical efficiency microturbine system
  - Recuperated gas turbine engine @ PR = 8
  - Exhaust flow @ 5 lb/s, ~700F



Cost of Electricity Guided Economic Assessment

Acquisition & Operating Cost Drive Affordability

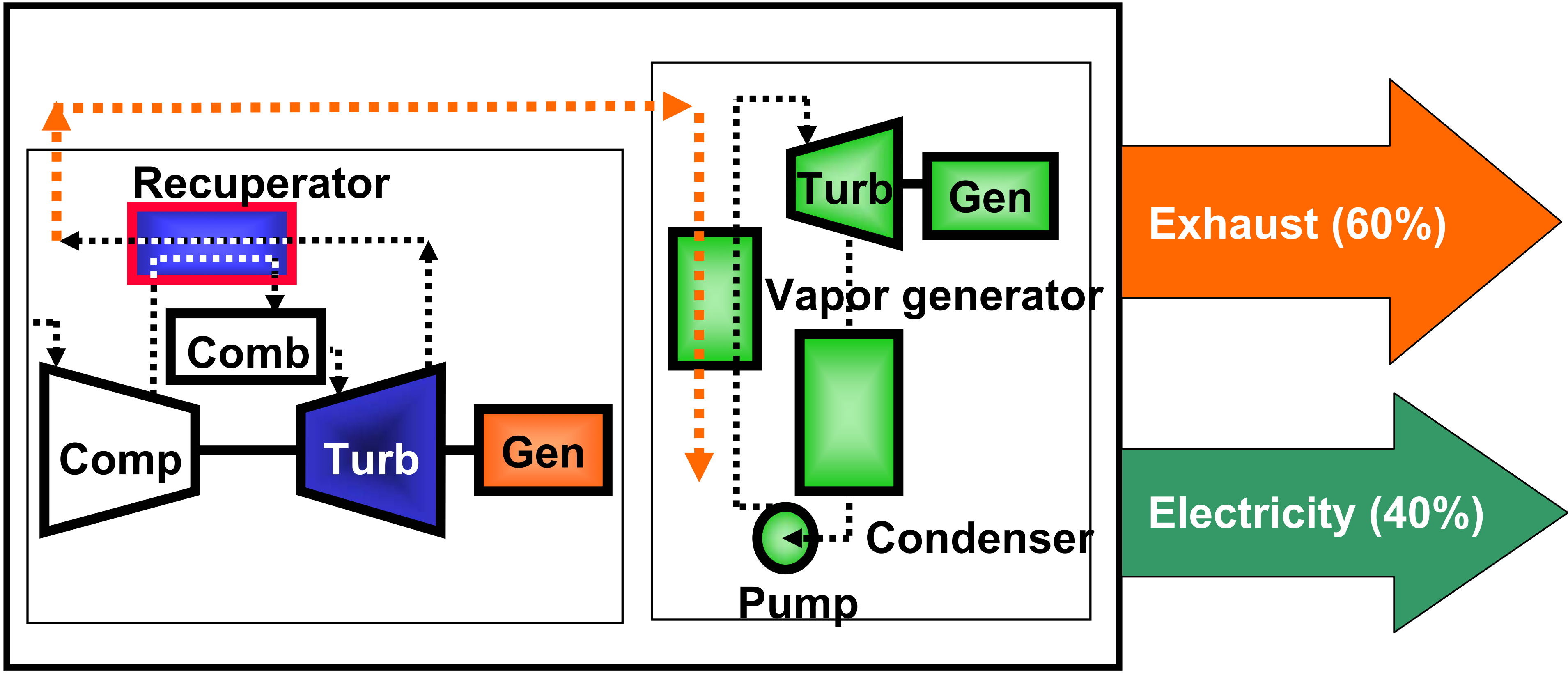
Cost of Electricity (COE) = Equipment $/Power/Hours
($/kW-hr) + Fuel $/Efficiency
+ Maintenance $



UTRC Advanced Microturbine System Adopted 3-Part Strategy

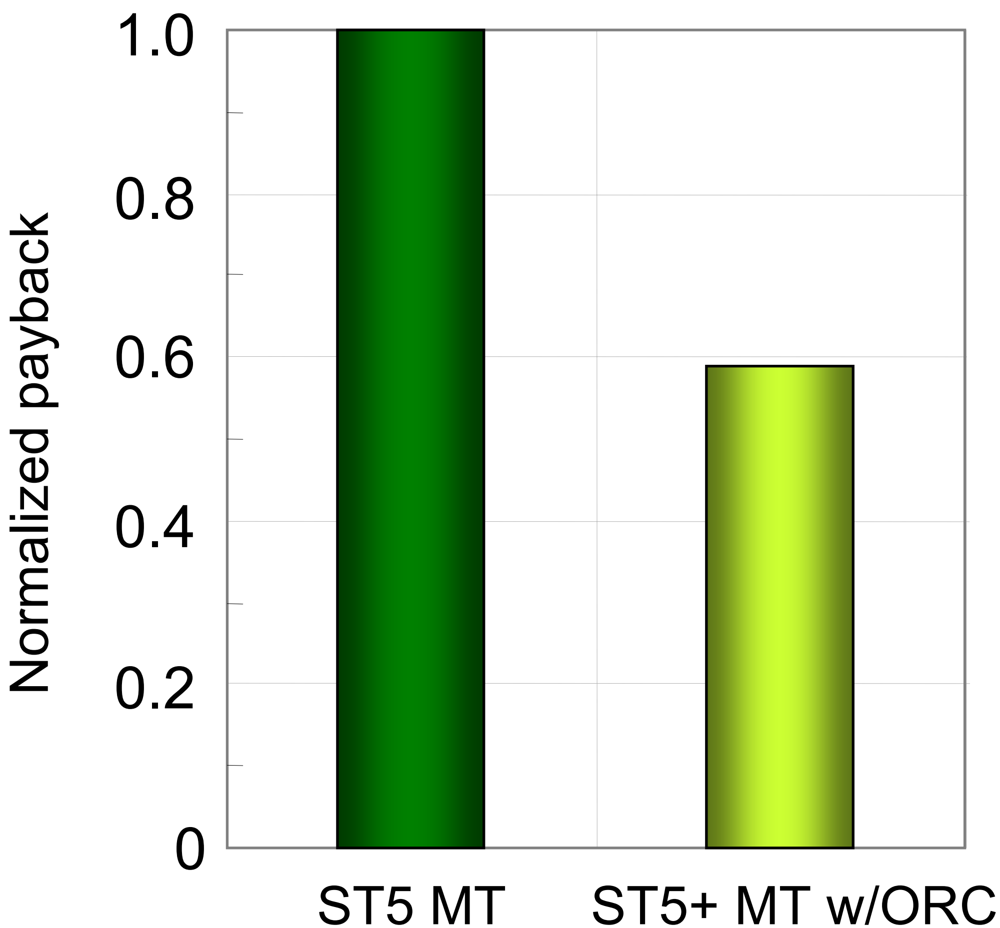
Organic Rankine Cycle Has Biggest Impact on System Efficiency

- Hotter Engine: Efficiency gain = 3 points
- Improved Electrical: Efficiency gain = 1 point
- Convert Waste Heat: Efficiency gain = 7 points



ST5+ Driven Microturbine Reduces Customer Payback by 40%

A higher-technology solution predicted as less affordable



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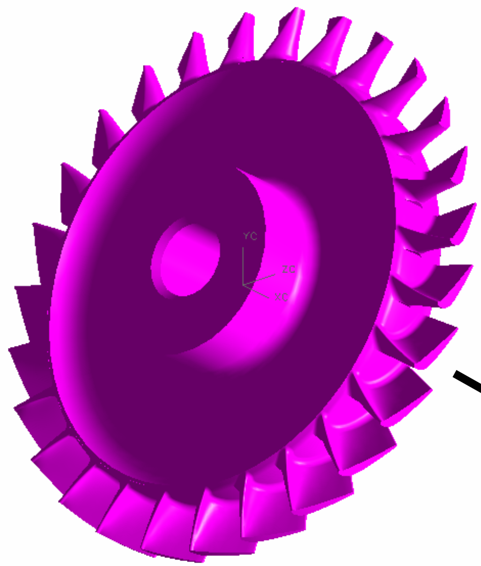
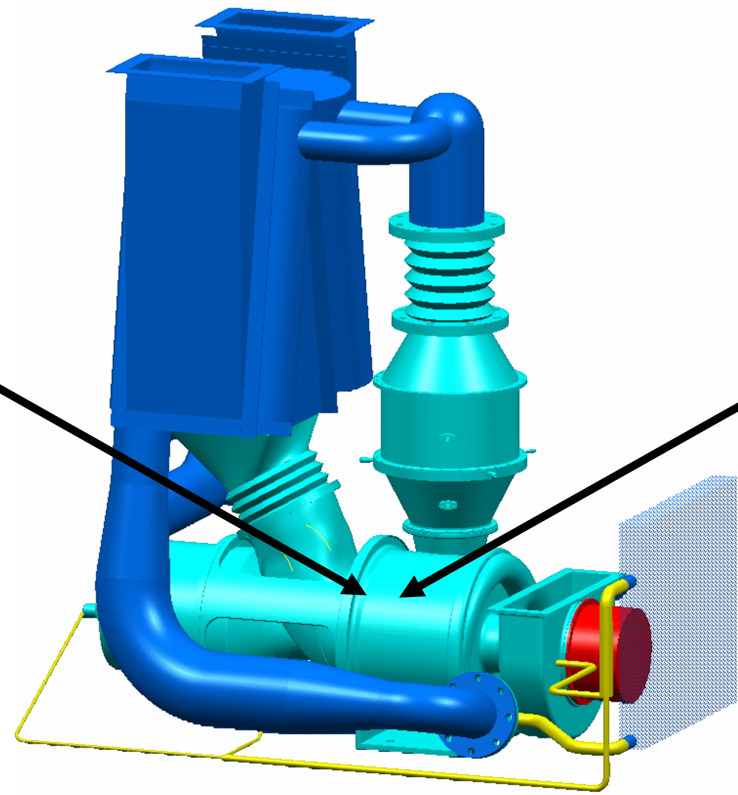
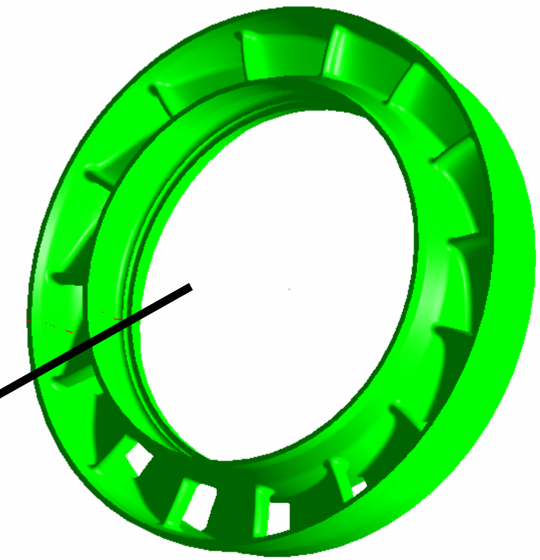
Ceramics Used for Vane and Integrally-Bladed Rotor (IBR)



Si_3N_4 IBR
Saint Gobain
(WB-NT154)





Integral Si_3N_4 Vanes
Kyocera (SN282)

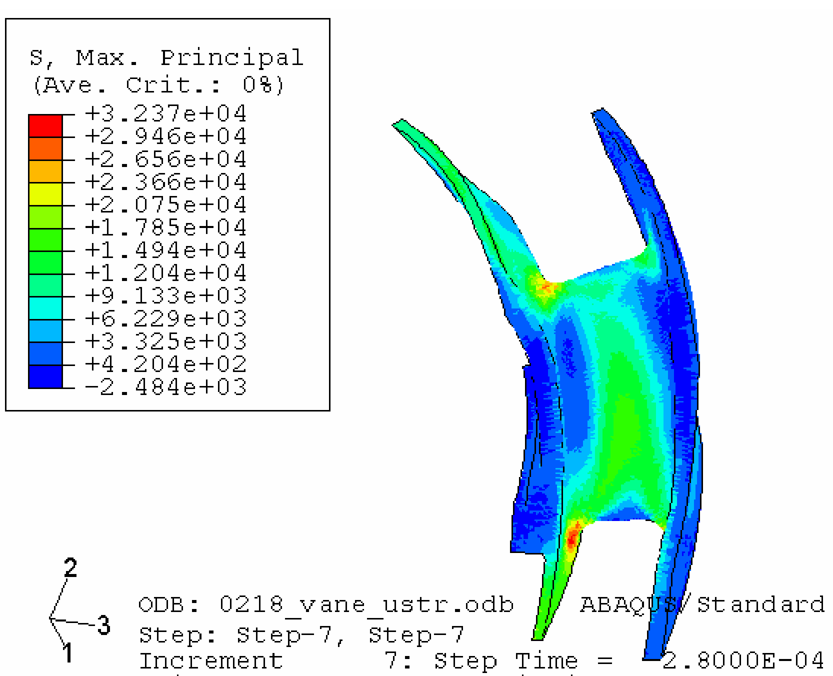
Government Labs/Companion Programs

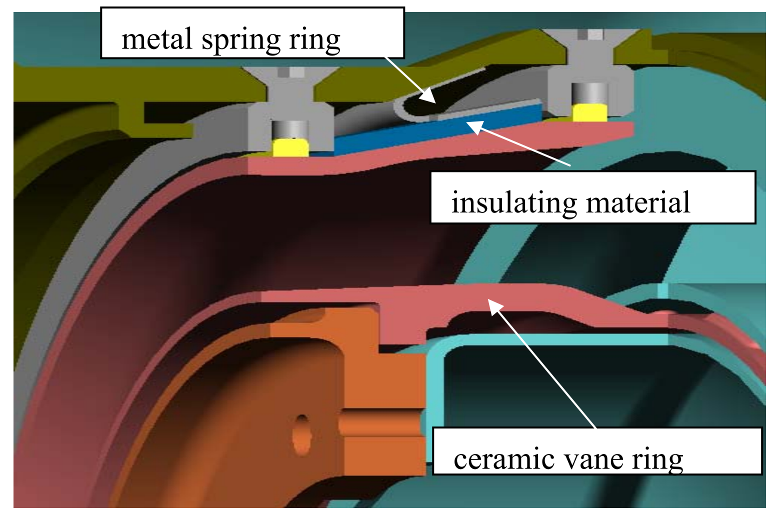
- ORNL-HTML – Characterizing silicon nitride materials, both with and without EBC
- NASA-UEET– Developing high temperature EBC for CMC
- Navy/DoE – Developing EBC for Silicon Nitride

Integral Ceramic Vane Ring Feasible

Silicon nitride integral vane ring

- Integral ring feasible with careful attention to mounting and fillet radii to minimize transient stresses
- Maximum temperature ~2200F @ SS
- Maximum tensile stress ~ 32ksi (220 MPa) in transient for continuous ring





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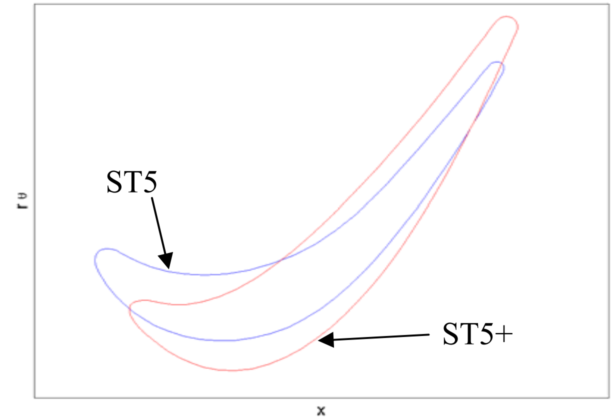
Ceramic Rotor Designed for Performance with FOD Tolerance

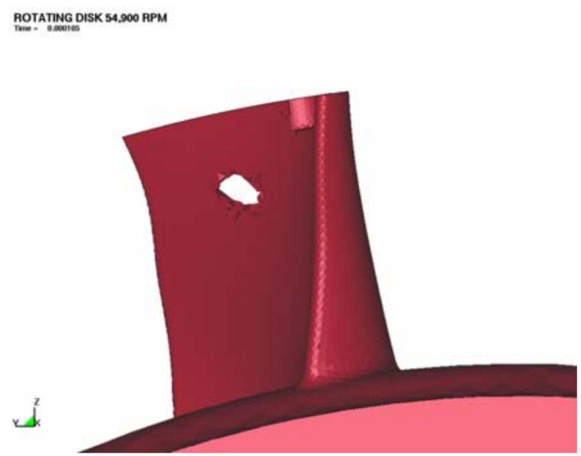
Silicon Nitride IBR Design

- Blade count reduced and trailing edge thickened
  - Nominal 2x increase in FOD resistance
  - Aerodynamic performance exceeds baseline because ceramic allows higher reaction
- Maximum blade temperature ~1920F
- Maximum bore stress ~72ksi (500 MPa)

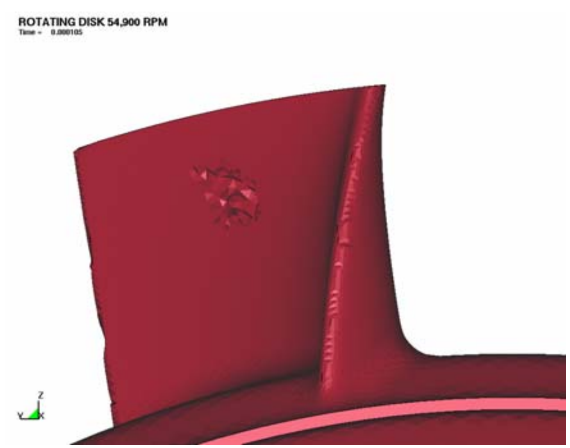


Blade Profiles

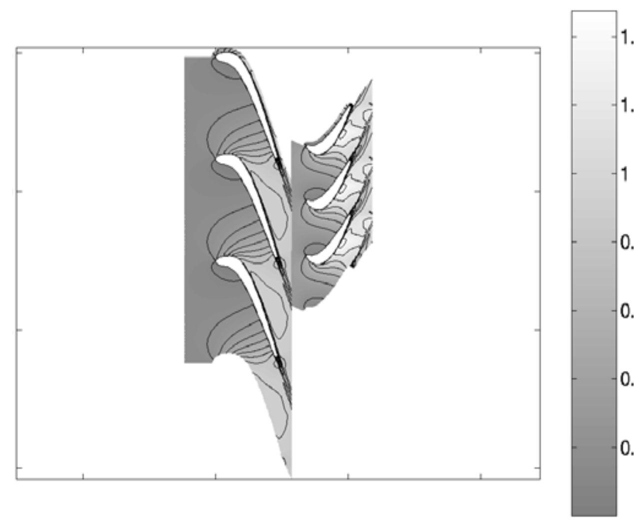
Effect of "TBC spall" impact on ceramic blades



ST5 blade shape: hole in blade



ST5+ blade shape: minimal surface damage



Mach No. Distribution

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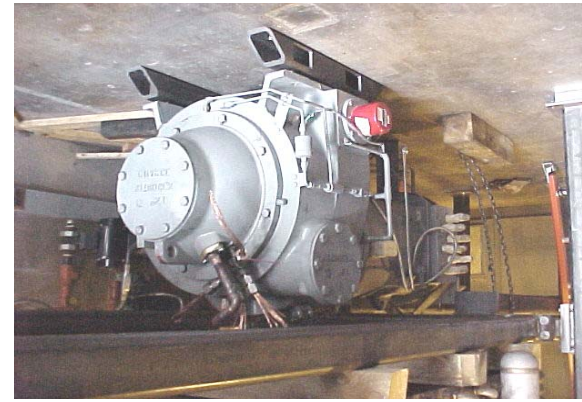
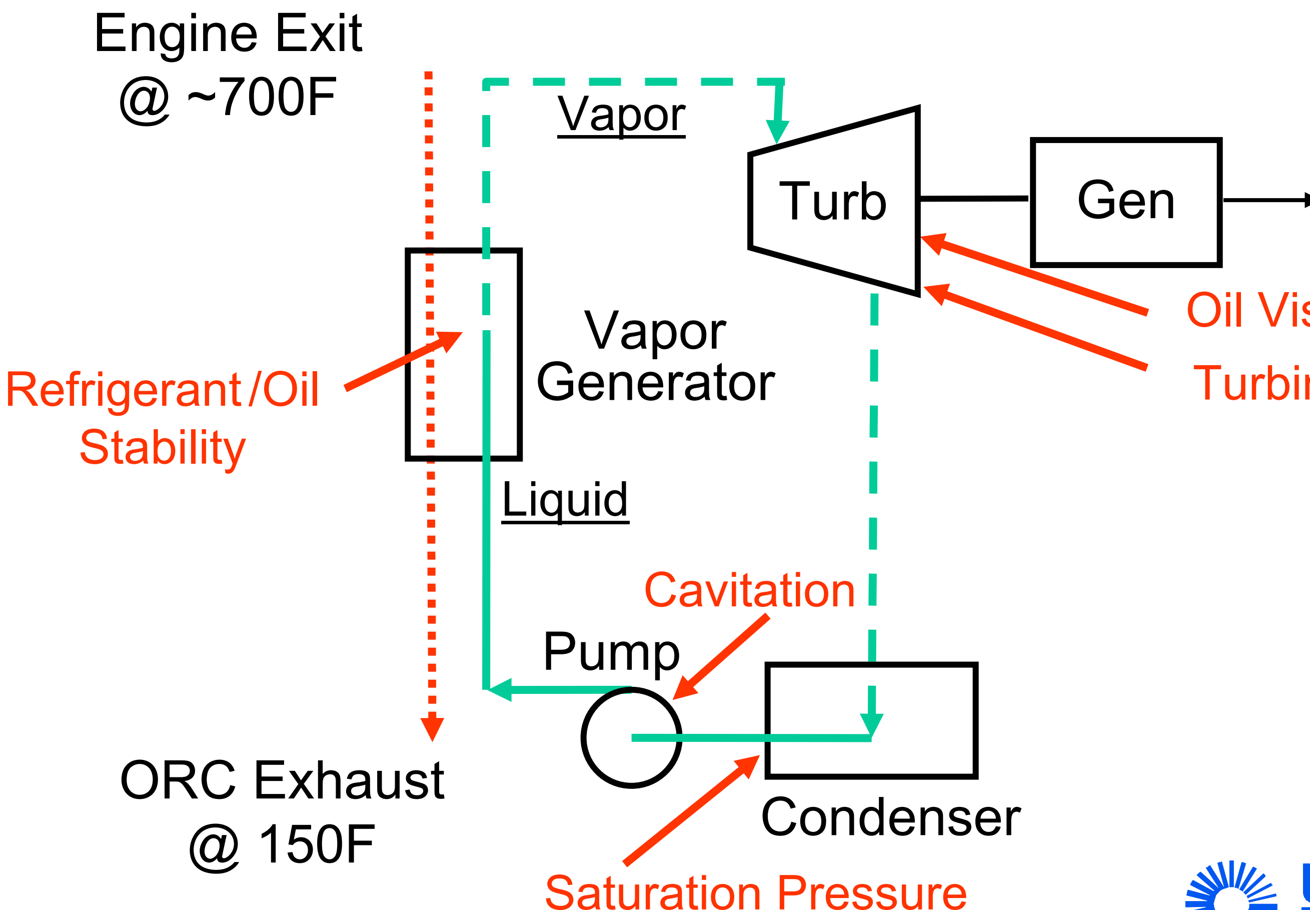
ORC System and Key Risks





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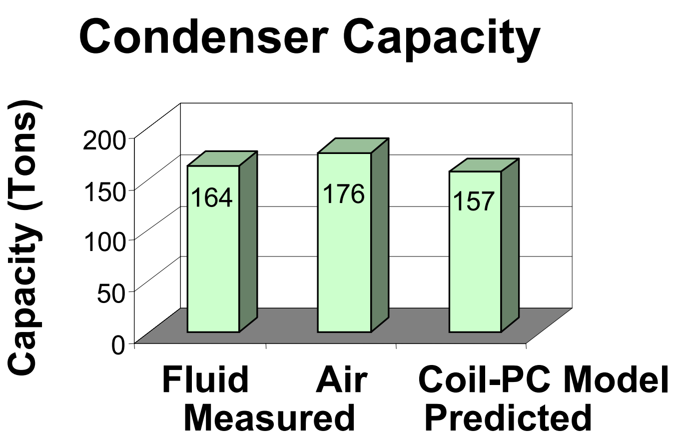
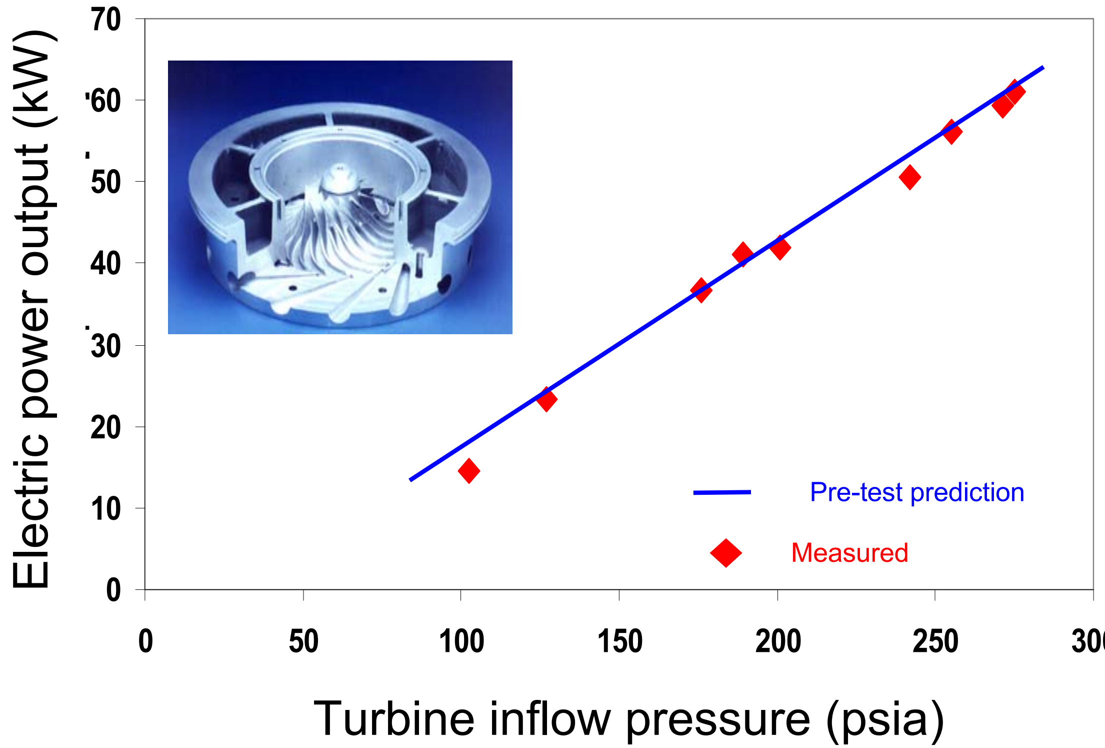
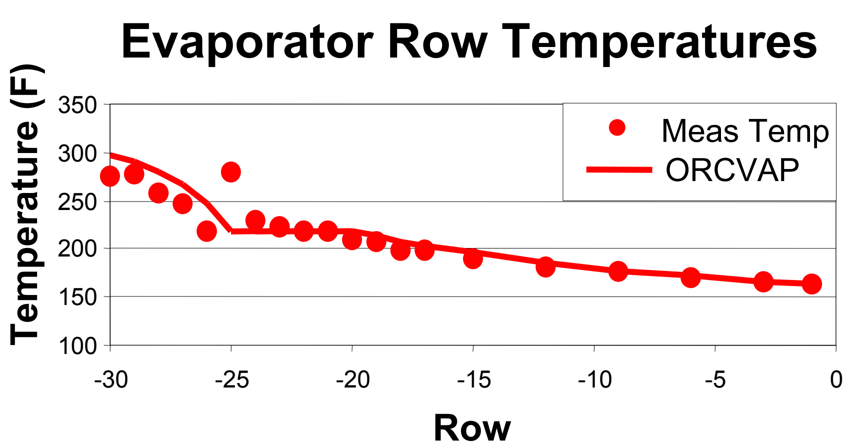
ORC Prototype Produced 60kW from Simulated ST5 Exhaust

System model validation in progress







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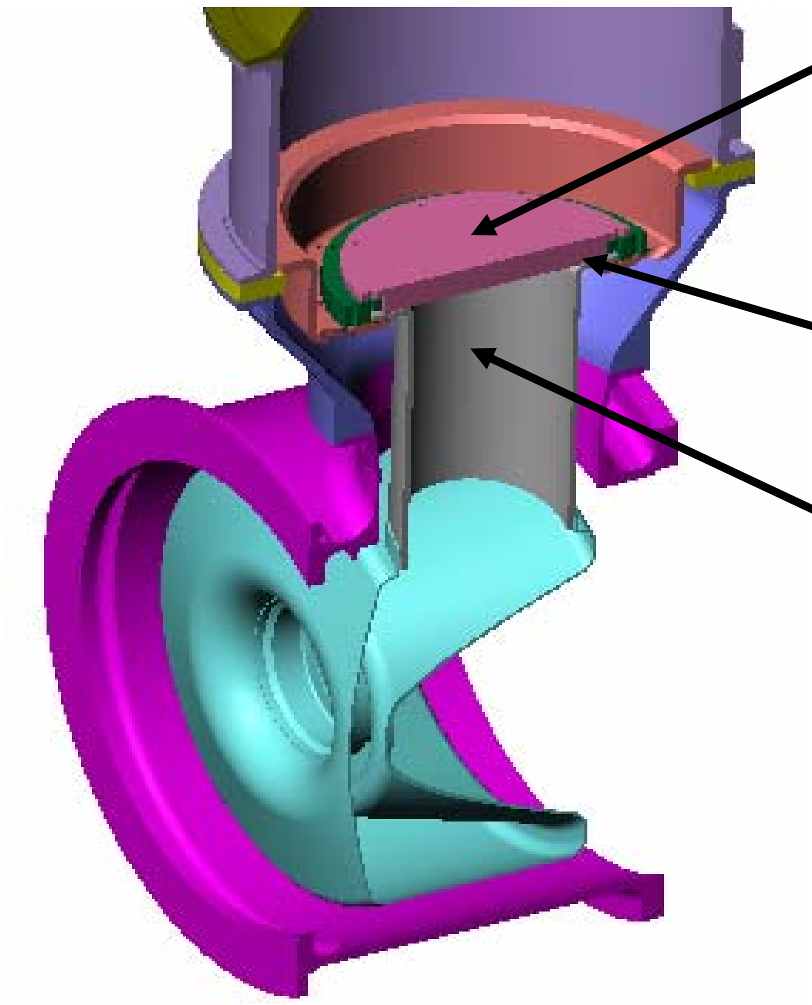
Stability of ORC Working Fluid Established

- No breakdown was observed in the pure fluid after 4 weeks exposure at 500F in presence of aluminum, copper and steel.
- Refrigerant grade Polyolester lubricant, mixed with the fluid to lubricate the turbine, can be used up to 350F without breakdown of oil or refrigerant and with no significant attack on aluminum, steel or copper.
- Applying creative additive chemistry based on jet engine lubricant formulations we have shown that the useful temperature of the refrigeration oil can be extended to 400F, improving ORC cycle thermal efficiency

Before

After
3 week exposure

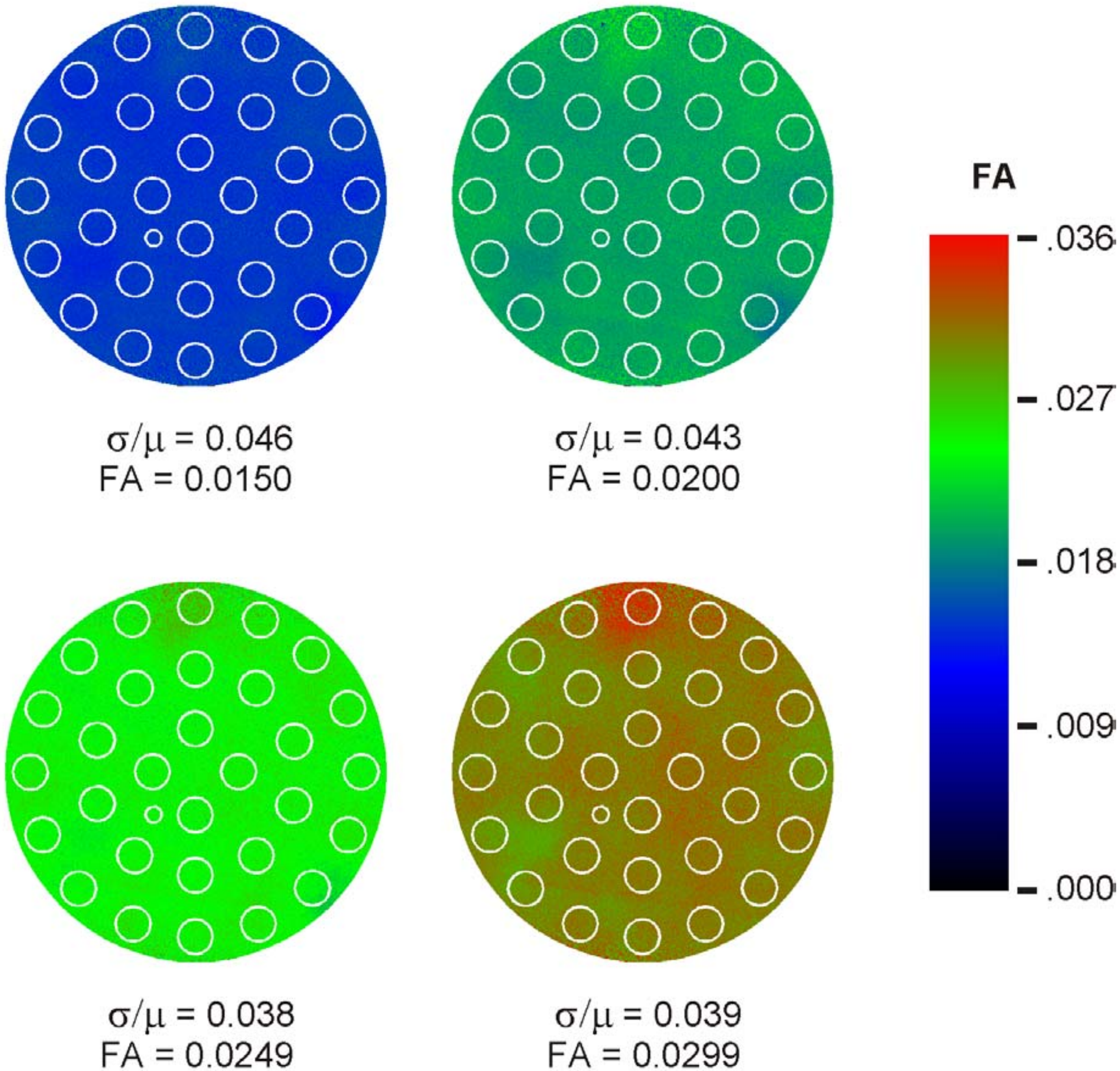
Low Emissions Premixing Combustor with Ceramic Liner



- Multipoint injection premixers designed for microscale mixing, low pressure loss, enhanced stability and turndown
- Liner attachments designed for life/stress requirements
- Ceramic liner for improved system durability
  - SiC liner material selected for affordability

High Fuel-Air Uniformity is Key to Low NOx

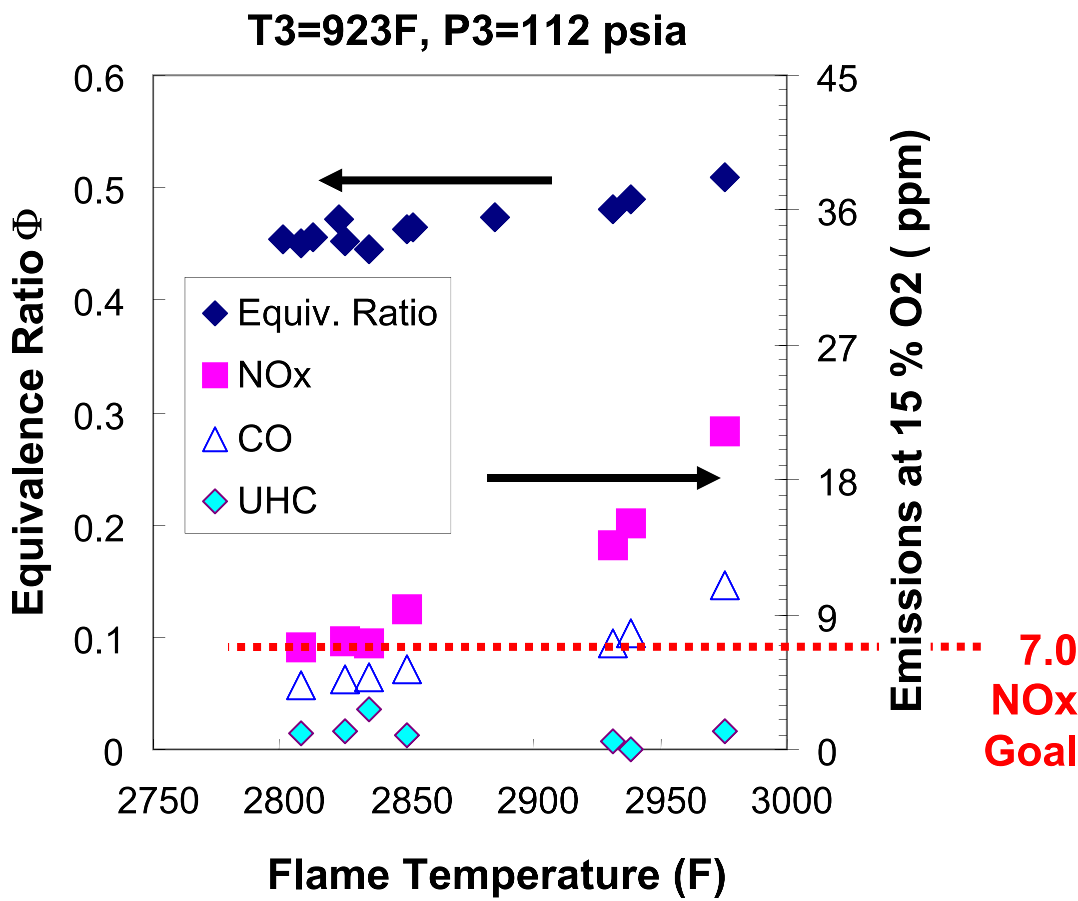
Excellent Mixedness (3-5%) Achieved over Power Range



Fuel Staging to Sustain Low Emissions 70-100% Power

Preliminary Tests Near 7 ppm NOx

- NOx < 7 ppm and CO & UHC < 10 ppm, although for T_{flame} window less than goal
  - Attained NOx, CO, and UHC < 9 ppm over ~75-100% power turndown
- Low pressure oscillations (<0.3 psi amplitude) achieved over turndown range
- Preferred staging strategy identified for emissions and stability margin
- Tests suggested design modifications



Future Key Milestones Lead to Field Demonstration

2002

- Demonstrate 80 kW from ORC with simulated ST5 exhaust (February 02 – **Completed**)
- Demonstrate 5-point increase in system electrical efficiency with ORC (August 02)
- Perform integrated microturbine/ORC test (September 02)
- Demonstrate combustor emissions technology for NOx<7 ppm and CO<10 ppm (November 02)

2003

- Demonstrate ceramic turbine performance in core engine (June 03)

2004

- Demonstrate 40% electrical efficiency, low NOx performance in engine system (April 04)

2005

- Initiate >4000 hr field tests to demonstrate life (January 05)

UTRC team is on a pathway for superior microturbine system

- Identified system to affordably enhance microturbine engine and convert waste heat to power with ORC
- Preliminary Design Reviews for Ceramic Turbine, Low Emissions Combustor and ORC affirmed their support of the system goals
- Technology risk-reduction activities are underway.
  - ORC prototype produced 80kW from ST5 engine waste heat.

- Advanced microturbine system has great public benefit
  - Expands customer choice for reliable, secure power
  - Provides option for reducing electricity cost, avoiding outages, and avoiding infrastructure investments
  - Produces lower NOx than diesel and larger gas turbine alternatives
  - Achieves fuel utilization >70% and reduced CO2 with CHP